FINITE ELEMENT MODELING TECHNIQUES FOR ANALYSIS OF VIIP

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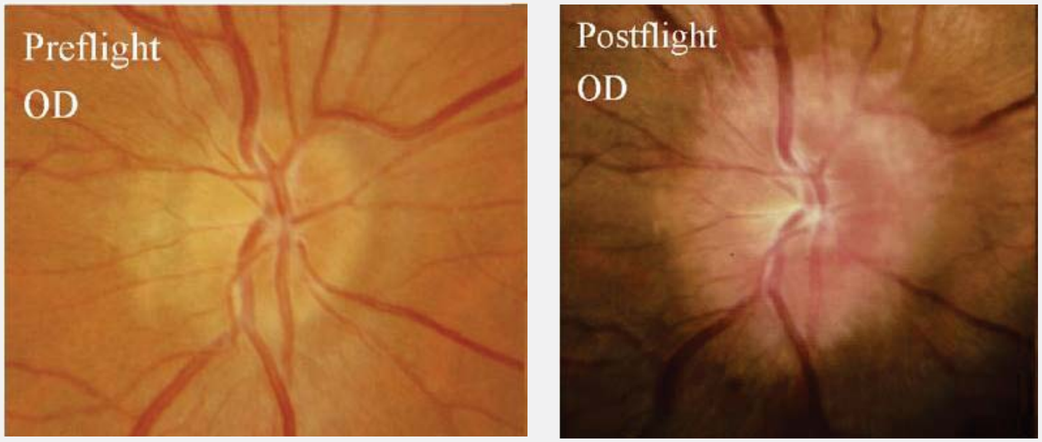
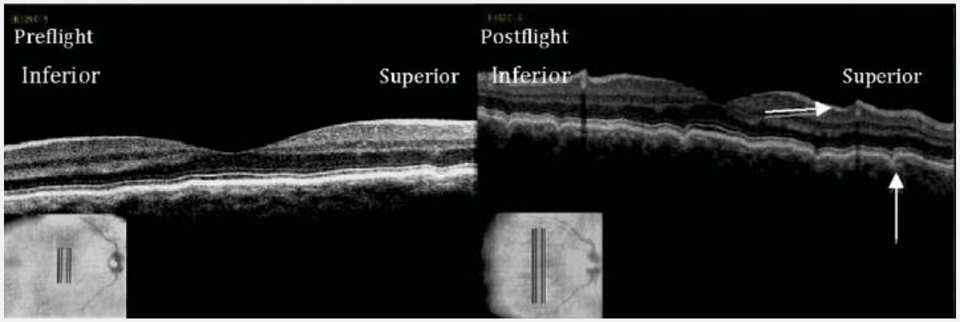
The Eye in Microgravity

- Clinical signs of microgravity in the eye and optic nerve:

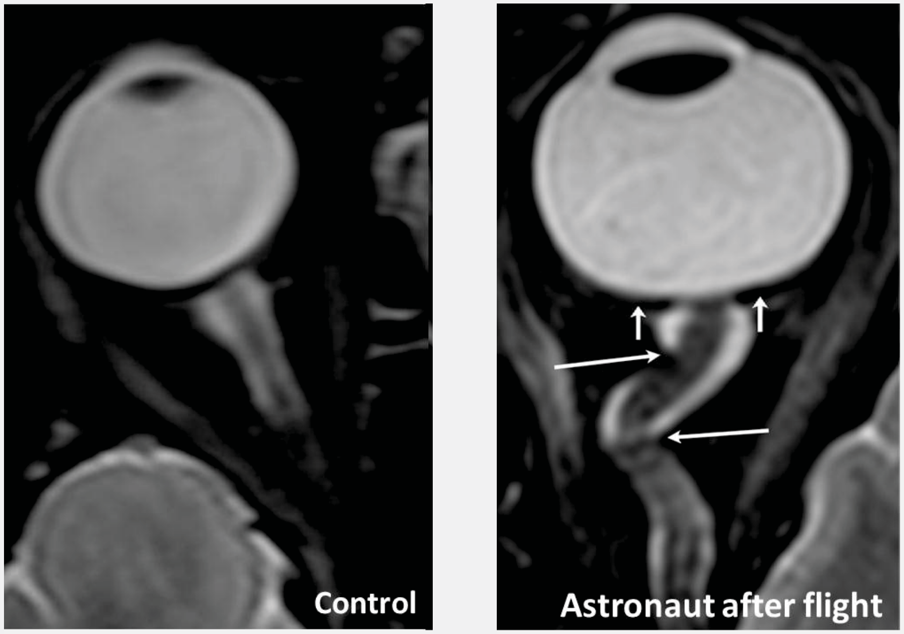
Grade 3 edema



Choroidal folds



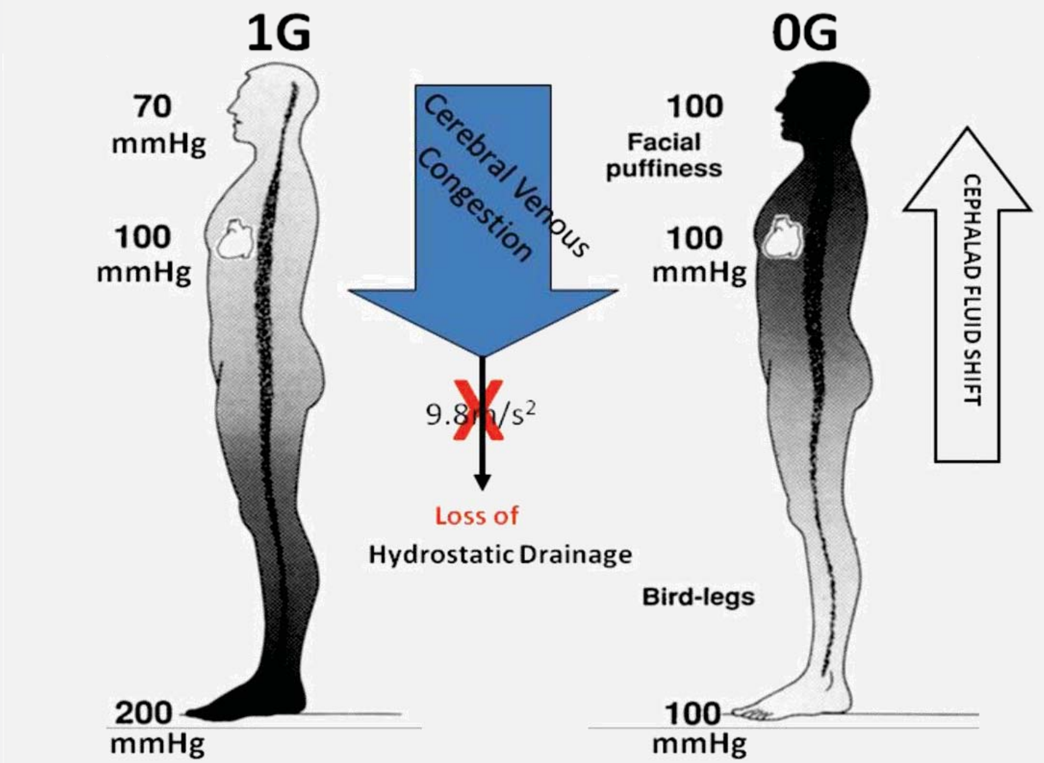
Posterior Globe Flattening
Optic Nerve 'kinking'



~Mader et al. 2011; Kramer et al. 2012

Hypothesis

- Cephalad fluid shifts in microgravity affect intracranial and intraocular pressures, leading to altered biomechanical loads on the connective tissues of the posterior globe and optic nerve sheath.



~humanresearchroadmap.nasa.gov

Goal & Approach

- Goal: To model the response of the lamina cribrosa and optic nerve head (ONH) to elevated intracranial pressure (ICP)

- Finite Element Analysis (FEA)
  - Simulates effects of loads (pressures) on tissues with complex anatomy/material properties
  - Previously used to understand how IOP-induced changes affect the stresses and strains in the lamina cribrosa and ONH

Initial Steps

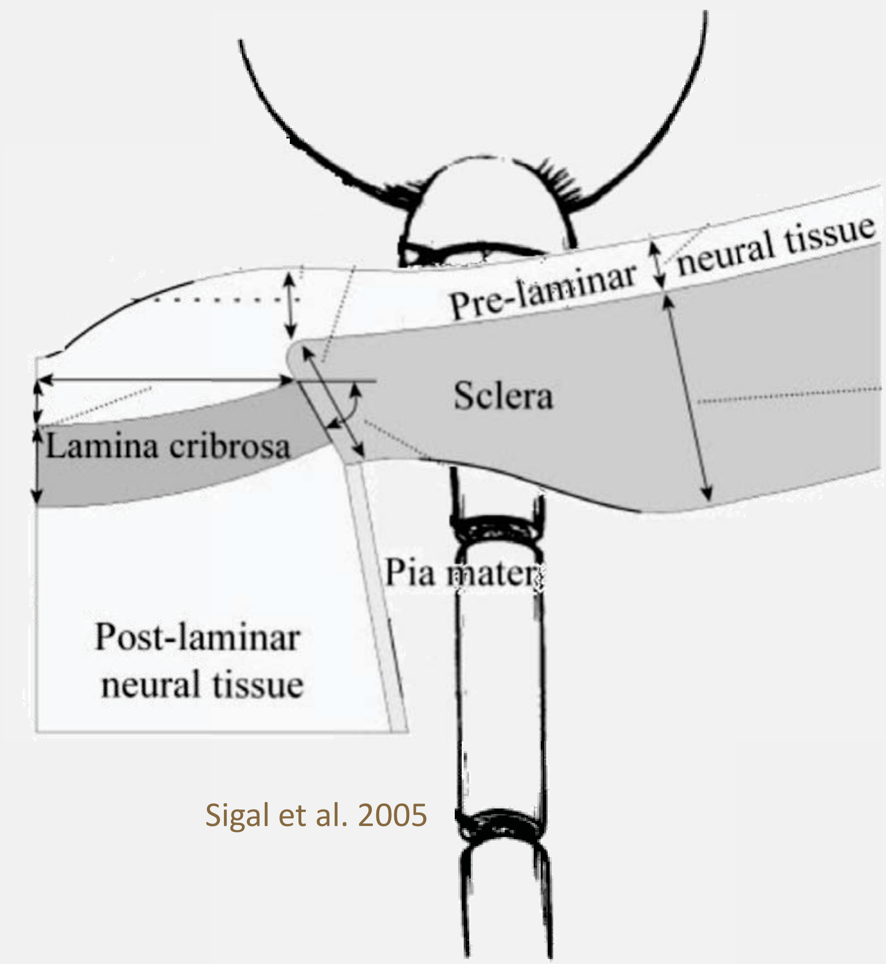
1. Develop geometry of the posterior eye
   – Including all relevant tissue components

2. Perform a mesh convergence study
   – To ensure mesh independence

3. Simulate pressures estimated to occur in microgravity

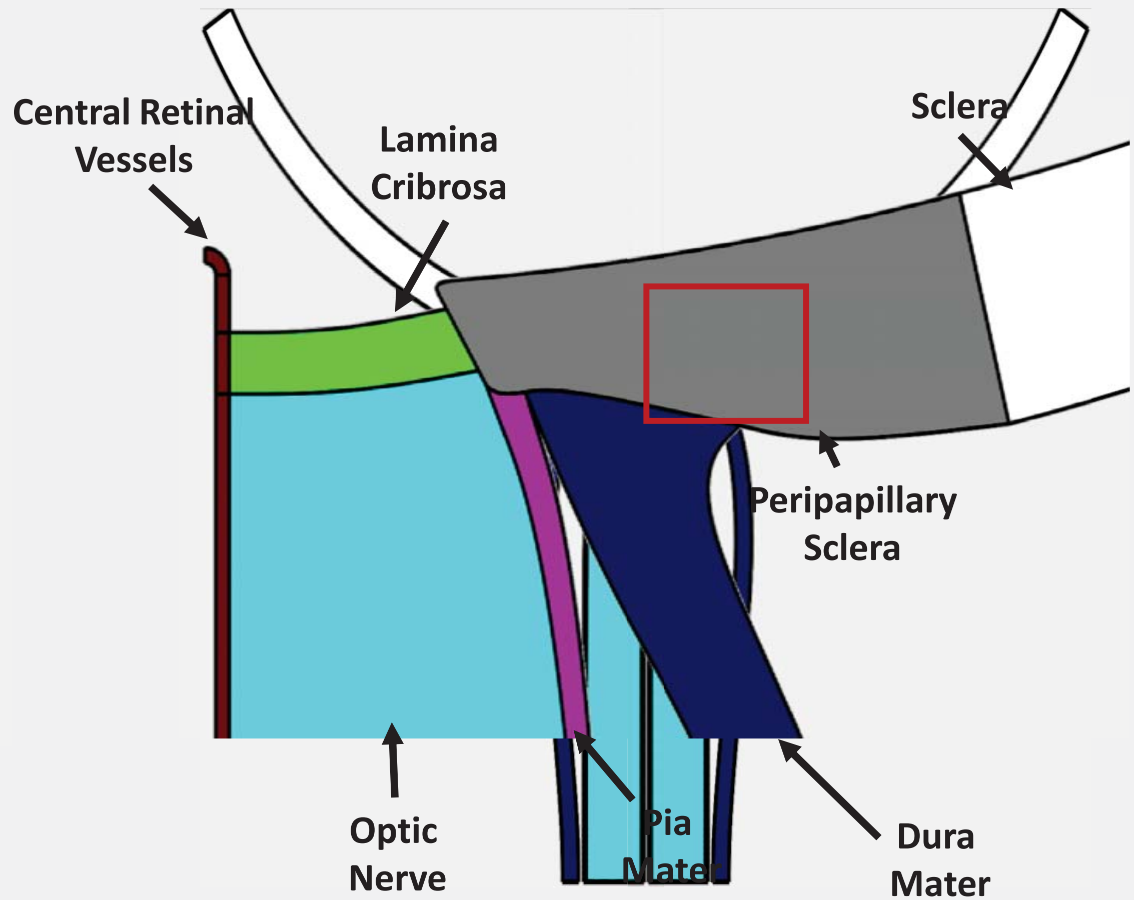
Optic Nerve Head (ONH) Geometry

- Based on models of Sigal et al., 2005



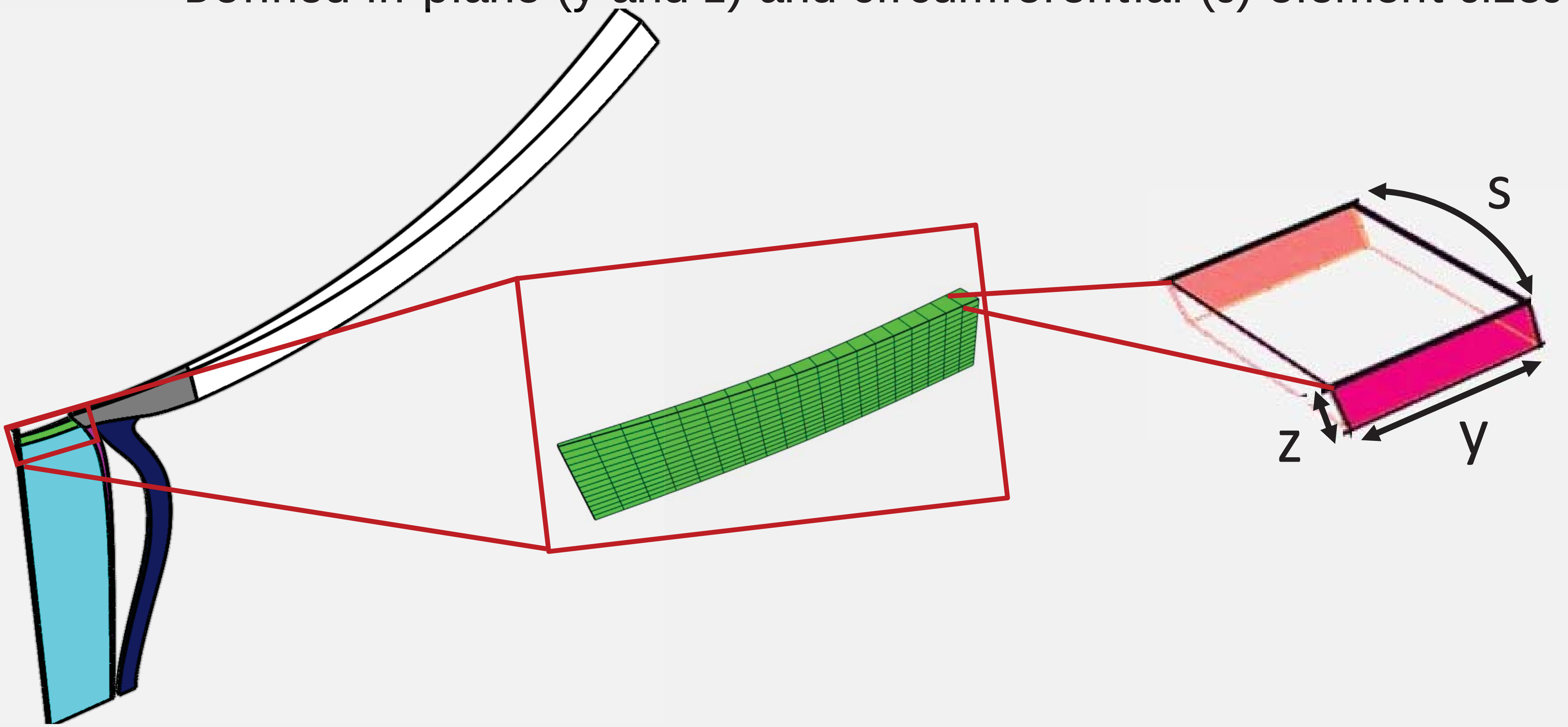
Sigal et al. 2005

Adopted from Liu and Kahn 1993



Geometry Continued

- Our anatomical geometry is axisymmetric but it was required to be modeled as a 3D wedge in the FE solver (FEBio)
  - Defined in-plane (y and z) and circumferential (s) element sizes



Model Overview

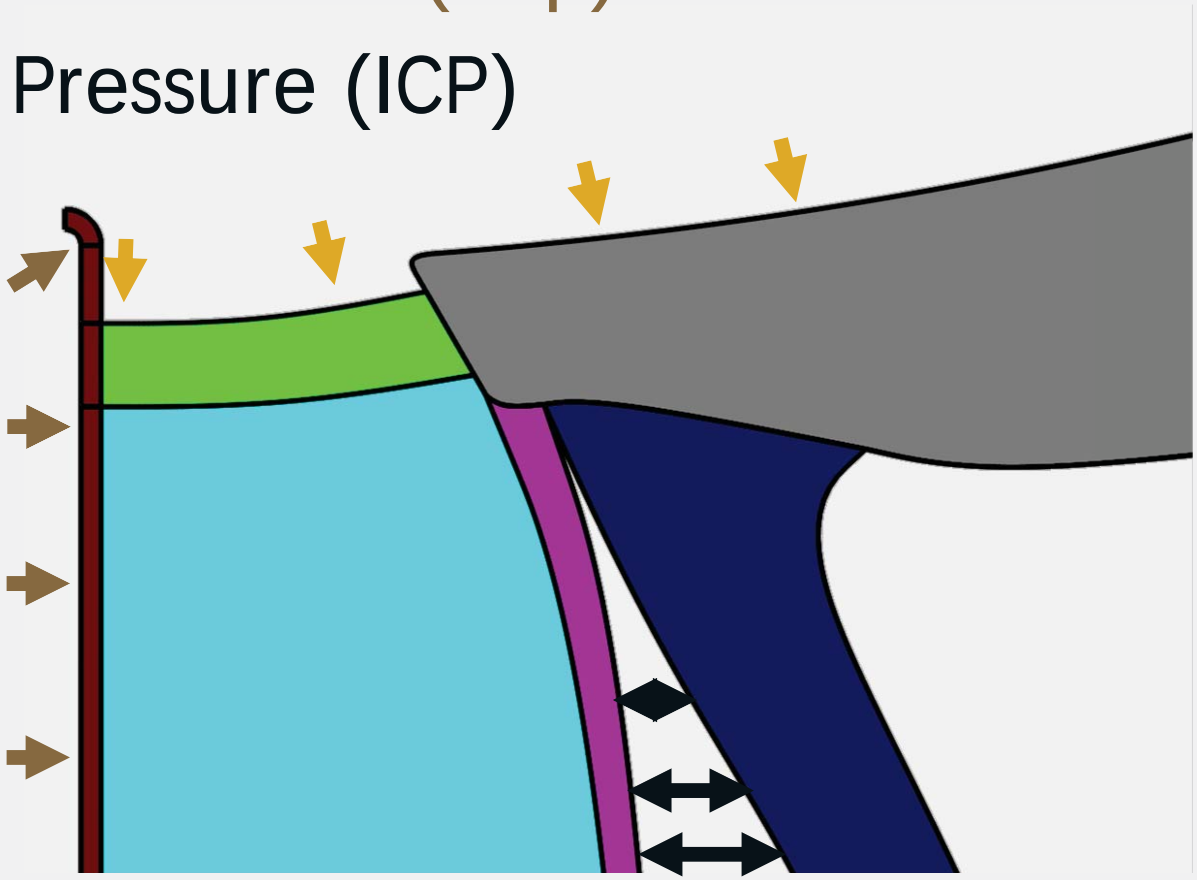
- All tissues were modeled as isotropic, linear-elastic and incompressible.

Component	Modulus (MPa)
Sclera	3.0
Peripapillary sclera	3.0
Lamina cribrosa	0.3
Optic nerve	0.03
Pia mater	3.0
Dura mater	1.0
Central retinal vessel	0.3

~ Raykin et al. 2013; Sigal et al. 2004; Sigal et al. 2005

Boundary Conditions

- Intraocular Pressure (IOP)
- Retinal Vessel Pressure (RVp)
- Intracranial Pressure (ICP)

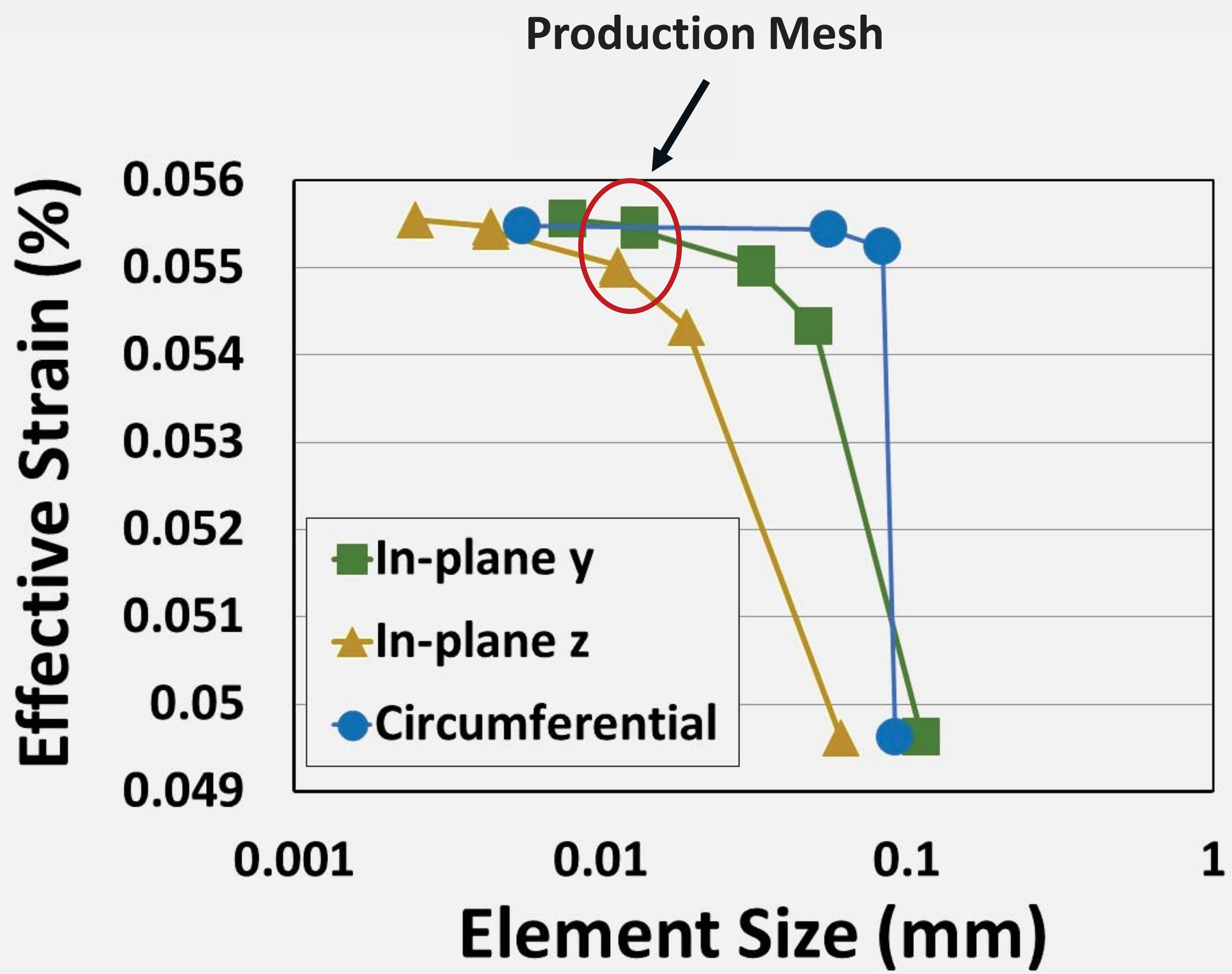


Convergence Overview

- The average effective strain for each tissue region was calculated for each mesh density.
- **Convergence Criteria:** Our production mesh was defined as having <5% relative error in the average effective strain from our most refined mesh.

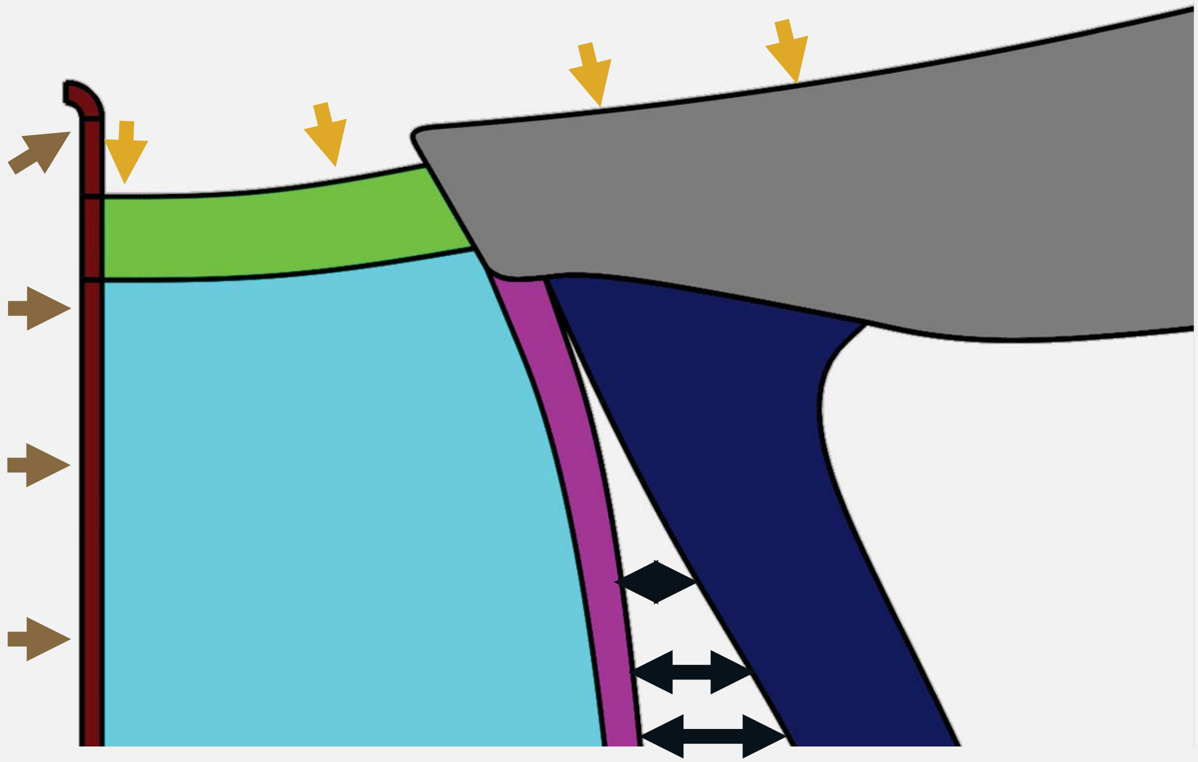
Component	Number of Elements (Hexahedral)
Sclera	689 – 7589
Peripapillary sclera	560 - 21145
Lamina cribrosa	265 - 13565
Optic nerve	8445 - 52147
Pia mater	662 – 53662
Dura mater	1835 – 44035
Central retinal vessel	243 - 126177

Lamina Cribrosa Convergence Plot



Estimated Pressures in Microgravity

- Intraocular Pressure (IOP) – 15 mmHg
- Retinal Vessel Pressure (RVp) – 55 mmHg
- Intracranial Pressure (ICP) – 30 mmHg



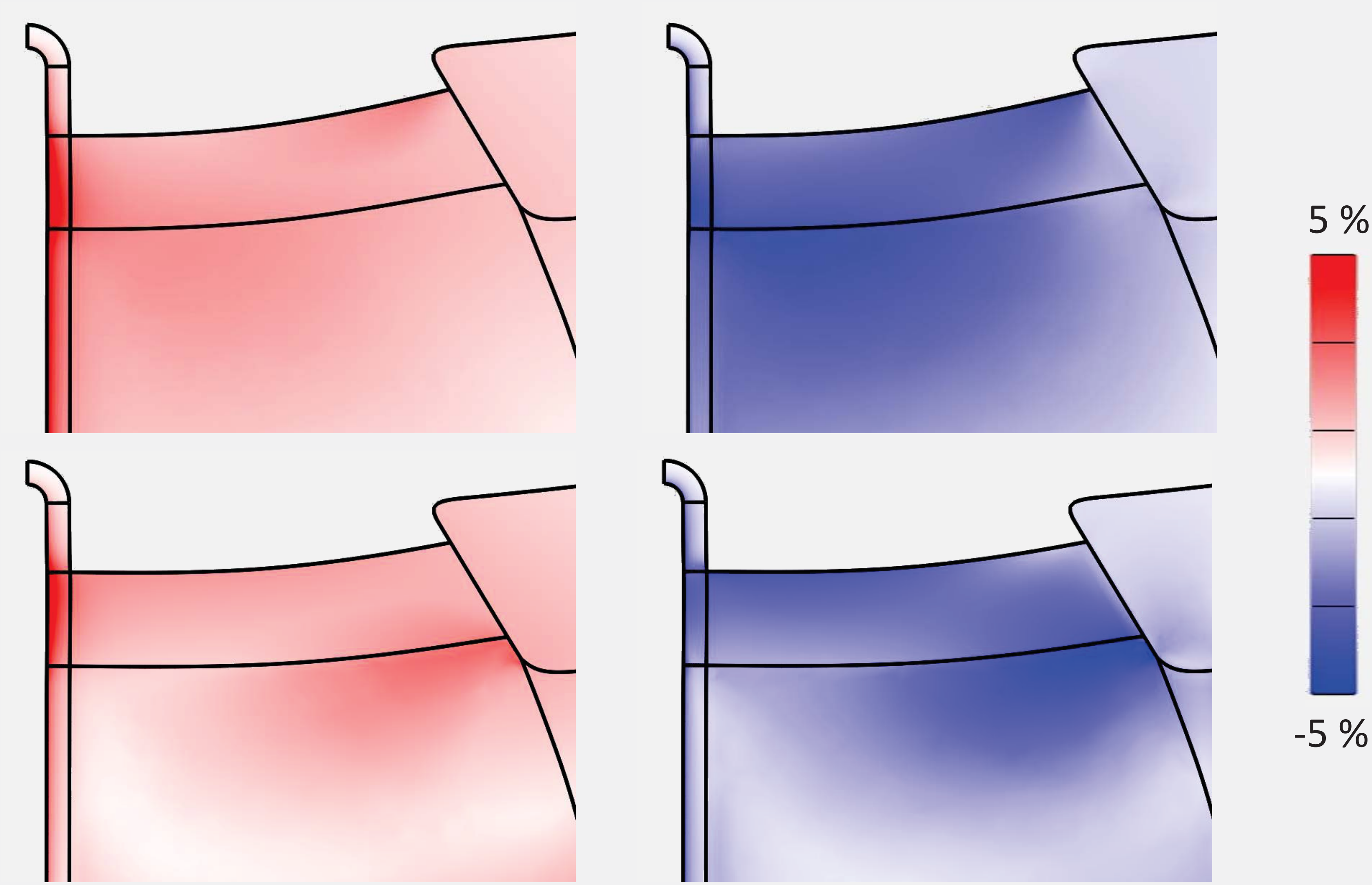
~ Alexander et al. 2012; Mader et al. 2011

Linear Elastic Model

First Principal Strain | **Third Principal Strain**

ICP: 0 mmHg

ICP: 30 mmHg



Conclusions

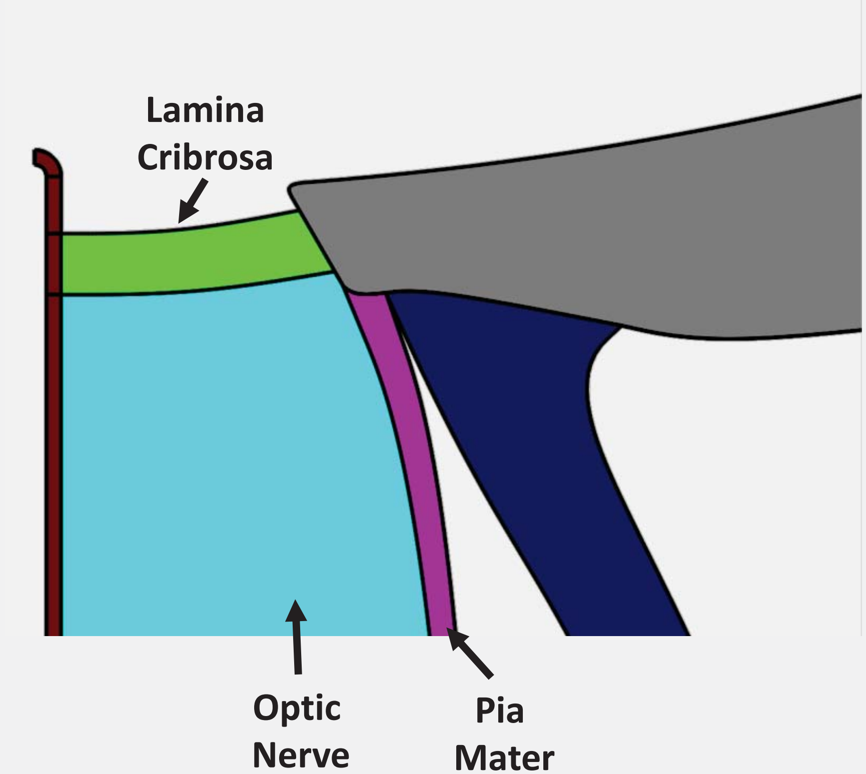
- Developed a physiologically relevant model of the posterior eye and optic nerve sheath
  - Performed a mesh convergence study
- We observed that elevating ICP alters the loading conditions in the optic nerve head
  - This may activate mechanosensitive cells and lead to a remodeling of the optic nerve sheath
- However linear-elastic materials may not completely describe the loading conditions of the eye in microgravity.

Poroelastic Models

- We explored implementing poroelastic materials and fluid loading conditions because:
  - The intraocular, retinal vessel, and intracranial pressures are generated by fluids
  - Poroelastic models allows volumetric changes when subjected to a fluid pressure
  - Fluid movement occurs between and within each tissue

Poroelastic Simulations

- Simulated the IOP and ICP as fluid pressures
- We modeled the components of the optic nerve head as poroelastic
  - The lamina cribrosa, optic nerve, and pia mater were poroelastic with a permeability of 0.001 $mm^2/MPa*s$

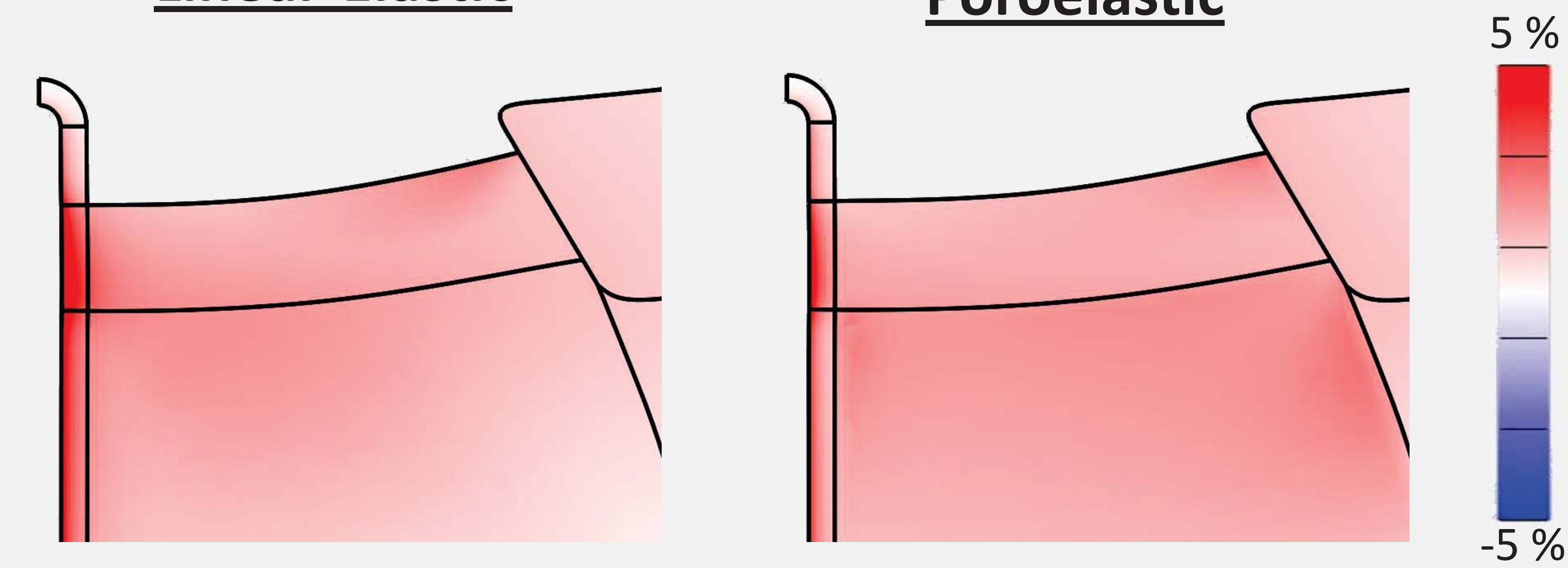


~ Raykin et al. 2013

First Principal Strain

Linear-Elastic **Poroelastic**

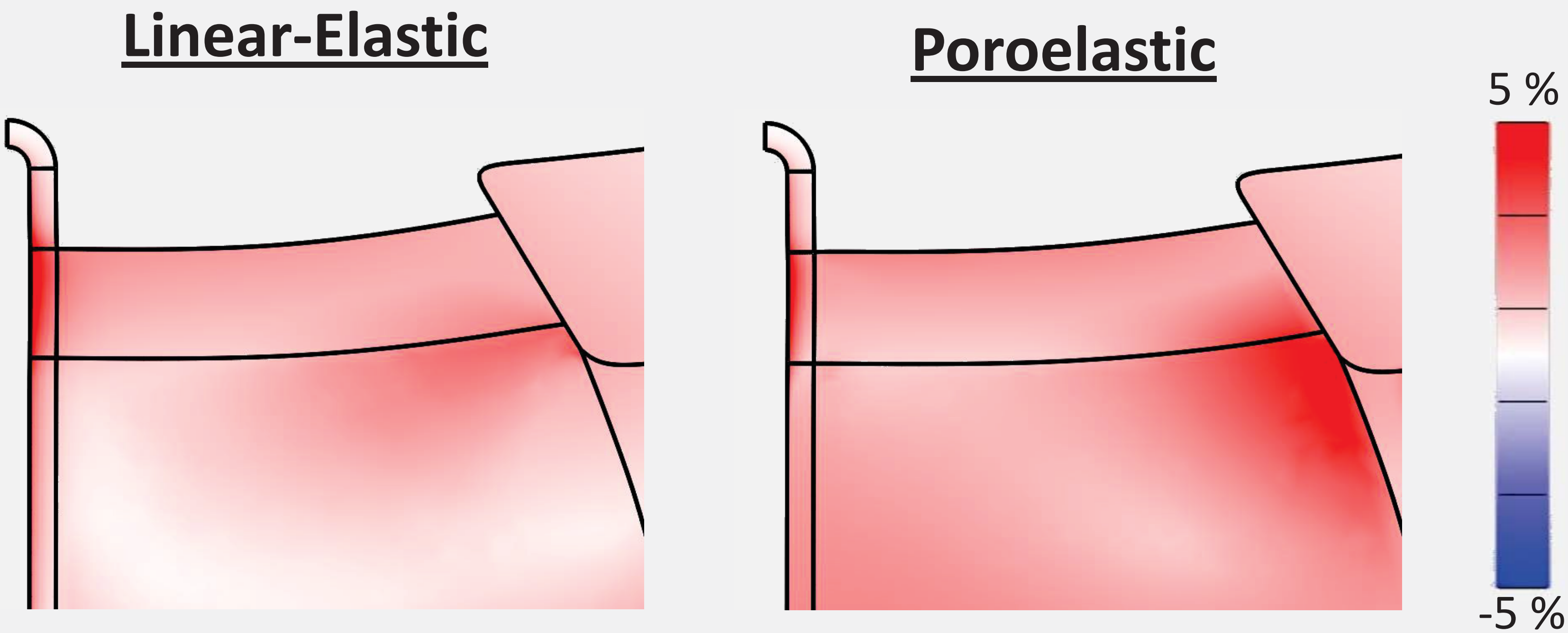
ICP: 0 mmHg



	Linear-Elastic	**Poroelastic**	
	Mean Strain	Mean Strain	Percent Difference
Lamina Cribrosa	1.64%	1.5%	2%
Optic Nerve	1%	1.4%	10.4%

First Principal Strain

ICP: 30 mmHg



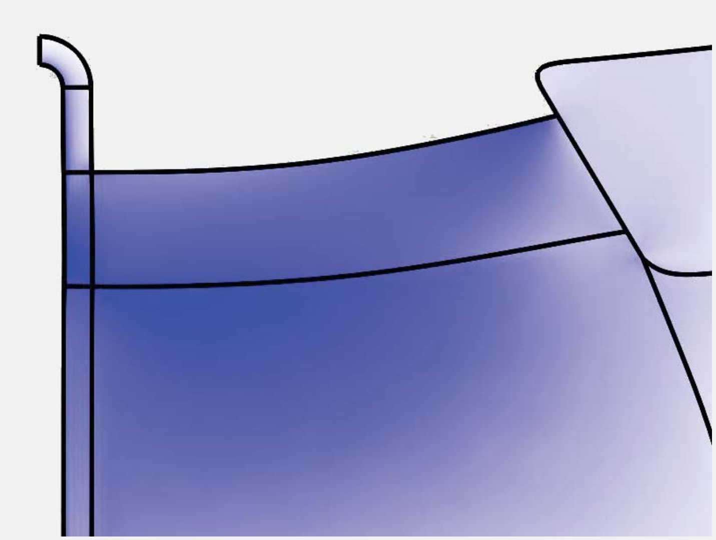
	Linear-Elastic	Poroelastic	
	Mean Strain	Mean Strain	Percent Difference
Lamina Cribrosa	1.5%	1.7%	2.4%
Optic Nerve	1.3%	2.1%	16.3%

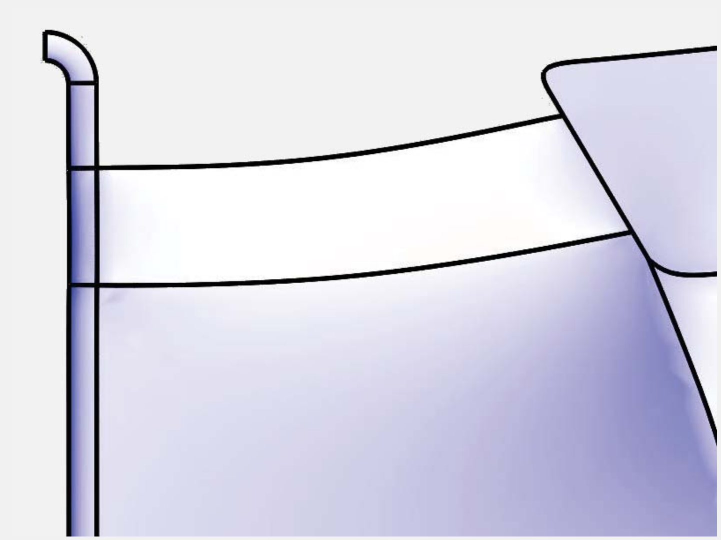
Third Principal Strain

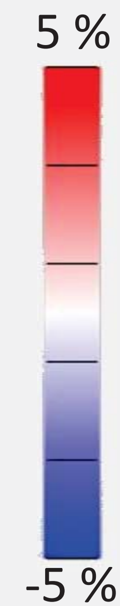
Linear-Elastic

Poroelastic

ICP: 0 mmHg





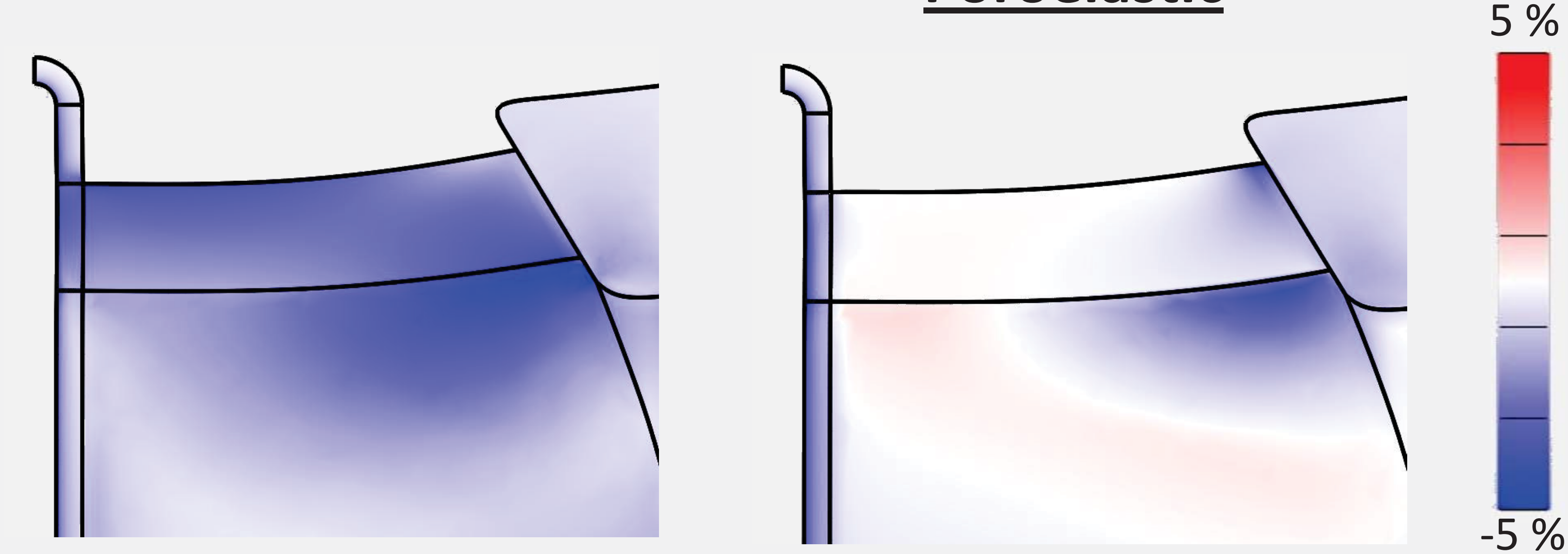


	Linear-Elastic	**Poroelastic**	
	Mean Strain	Mean Strain	Percent Difference
Lamina Cribrosa	-2.8%	-0.05%	24.5%
Optic Nerve	-1.7%	-1.0%	11.1%

Third Principal Strain

ICP: 30 mmHg

Linear-Elastic **Poroelastic**



	Linear-Elastic	Poroelastic	
	Mean Strain	Mean Strain	Percent Difference
Lamina Cribrosa	-2.6%	-0.3%	22.2%
Optic Nerve	-1.6%	-0.44%	18.2%

Conclusions

- We observed large differences in the strains between the linear-elastic and poroelastic model simulations

- Poroelastic models may be more physiologically relevant because they can apply fluid pressures and allow fluid flow within tissues
  - However, we need more information on the permeability of ocular structures to implement more accurate FE models

Acknowledgements

- DeVon Griffin